A novel integrated micro-force measurement system for plane-plane contact research.

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The evaluation of plane-plane contact force has become a big issue in micro/nano research, for example in micro-assembly. However with the lack of effective experimental equipments, the research on plane-plane contact has been limited to theoretical formulations or virtual simulation. In this paper, a micro-force sensor and precision parallel robot integrated system is proposed for the micro-force measurement of plane-plane contact. In the proposed system, the two objects are fixed on the parallel robot end-platform and the micro-force sensor probe tip, respectively, and the high precision robot system is employed to provide six degree-of-freedoms motion between both objects. So it is convenient for the micro-force measurement between the planar objects with different orientations. As a significant application, the proposed system is utilized for measurements of pull-off force between planar objects, in which the validation of the system is demonstrated in practice. The proposed micro-force measurement system is generic, which can be extended to a variety of micro-force measurements in plane-plane contact.

I. INTRODUCTION

The invention of the atomic force microscope (AFM) and the development of other micro-force sensors provide important tools for the surface science and interface technology [1-9]. As a significant application, these micro-force sensors are frequently used in a variety of micro-forces measurement such as adhesion force, friction force, and other interaction forces between the micro-objects. More attention of this research is focused on the sphere-sphere or sphere-plane contact studies but not the plane-plane case, because sphere contact is the main research case for pharmacy science, powder technology and chemistry engineering, in which the research objectives concerned are particles or powders. Currently, the plane-plane contact also has been becoming a big issue in the research and actual applications. For example, in the handling operation in micro-assembly, the contact between the gripper and the objects always generates adhesion force, which will influence the assembly precision and even make it failure. In fact, the successful application of these sensors on sphere contact cannot be transferred directly into plane-plane contact research, since it is very difficult to implement plane-plane contact research directly on a general AFM device or a commercial micro-force sensor setup in which a precise alignment between surfaces can not be realized. With the lack of effective experimental equipments, research on plane-plane contact has been limited only to theoretical formulations or simulation, so a micro-force measurement system with generic purposes is urgently needed in the field of micro/nano research.

Some researchers make efforts to modify the AFM and the other commercial micro-force sensor systems or add accessories into the systems setup according to different applications. Bobji et al. [10] added a left-right combination lead screw as an accessory to the AFM measurement system for a tensile test of magnetic material. Tambe et al. [11] used a motorized stage as the specimen holder for fatigue study on thin films, which provides one linear degree-of-freedom to the specimen positioning. Tambe and Bhushan [12] modified a commercial AFM setup with a single-axis nano-positioning stage with maximum velocity of 10mm/s which is used for nano-scale friction studies at high sliding velocities. Tao and Bhushan [13] in their further research, improve the relative sliding velocity up to 200mm/s via employing a new linear stage for the nano-scale friction measurement based on AFM. Kim et al. [14, 15] reported their works on a new AFM system, in which the XY planar scanner as a very important accessory is introduced to minimize the Abbe errors during the AFM measurement. Rabenorosoa et al. [16] added two individual single-axis rotation positioners to a commercial micro-force sensor system to realize the alignment of two micro surfaces in order to investigate the related angle and preload influence effects to the micro-force. An interested topic about the friction and pull-off forces between two micro-surfaces is reported in Ando's article [17]. In his research, one of the objects is the flat surface of the AFM tip (0.7μm×0.7μm), and the other one is a two-dimensional arrays uniform intervals of 240 nm. The micro-forces measurement experiments have to yield to a 2.5^o orientation misalignment between the two micro-surfaces because of a lack of effective experimental equipments. So it can be seen that many efforts have been made to modify micro-force sensor systems via a variety of experiment configuration. However, a planar contact micro-force measurement platform for general research purposes is infrequently reported.

In this paper, a more generic micro-force measurement system for plane-plane contact study is proposed, in which a high precision six degree-of-freedoms parallel robot is integrated to work as a scanner and orientation adjuster, and a commercial micro-force sensor is employed as the force detect device. So some complicated research such as plane-plane contact study can be implemented in this proposed system.

II. MICRO-FORCE MEASUREMENT SYSTEM

A. Overview of the proposed system

FIG.1 shows the overview of the proposed micro-force measurement system. The robot integrated in the micro-force measurement system is a 6 degree-of-freedoms commercial parallel robot (product series: SpaceFab 3000 BS, MICOS, Germany [18]), which can provide decades millimeters motion range (50mm×12mm×100mm) and sub-micrometers precision (0.2μm translational resolution and 0.0005^o rotational resolution). So three rotation degree-of-freedoms can be used for orientation adjustment, and the other three translation degree-of-freedoms can be used for micro-force measurement motion. In order to increase the measurement accuracy, especially for the two objects' approaching and retracting, a single degree-of-freedom piezoelectric actuated stage (product series: P-611.ZS, PI, Germany [19]) with nanometer level resolution is fixed on the end-platform of the parallel robot system via a rigid holder, which provides high precision motion between the two objects to be measured. The micro-force sensor (product series: FT-G100, FemtoTools, Switzerland [20]) used in the system is a modified commercial device, which can be replaced in the proposed system by other sensors according to the different applications. FT-G100 is a micro-gripper with micro-sensor, which can be used as a pure micro-force sensor through removing the actuation part. The robot system and sensor system are fixed respectively on an anti-vibration table in order to effectively reduce the mechanical influence from the outside environment.

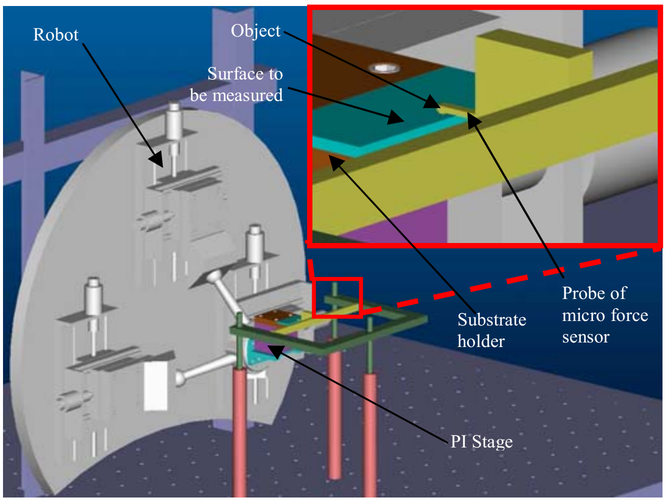

FIG. 1. 3D model of the proposed integrated micro-force measurement system.

B. System registration

Before the micro-force measurement implementation, a registration process should be carried out firstly. The so-called registration is to identify the relative position and posture of the object to be measured with respect to the measurement system. Since it can not be guaranteed that the object can be placed very precisely on the specified location of the proposed system (end-platform or micro-force sensor tip), it is very necessary to determine the relative position and posture between the objects on the end-platform of the robot system and on the micro-force sensor probe tip respectively. So in the registration process, a standard substrate with reference markers is adopted, which is rigidly mounted on the end-platform of the motorized stage (parallel robot + piezoelectric actuated stage). Via scanning the reference markers by the micro sensor, the relative position and posture between the force measurement system and the object to be measured can be identified. Although this registration process is quit complicated, it is obvious that it is very critical for the measurement, which is discussed in detail in [21]. After the registration, the proposed system can be used for various micro-force measurements.

III. PULL-OFF FORCE MEASUREMENT

As a significant advantage over the previous micro-force measurement systems, the proposed integrated device is attempted to perform a pull-off force measurement between two planar surfaces.

FIG.2 shows the current experiment setup for the pull-off force measurement between two surfaces. Besides the proposed integrated micro-force measurement configuration, the auxiliary light source and camera system is introduced for the assistance of the experiments. The two surfaces to be measured in the experiment are the flat glass surface and the silicon microcomponent surface shown in the figure. The glass surface is fixed on the piezoelectric stage above the robot system and the silicon microcomponent (400µm×400µm×100µm) is glued on the probe tip of the micro-force sensor.

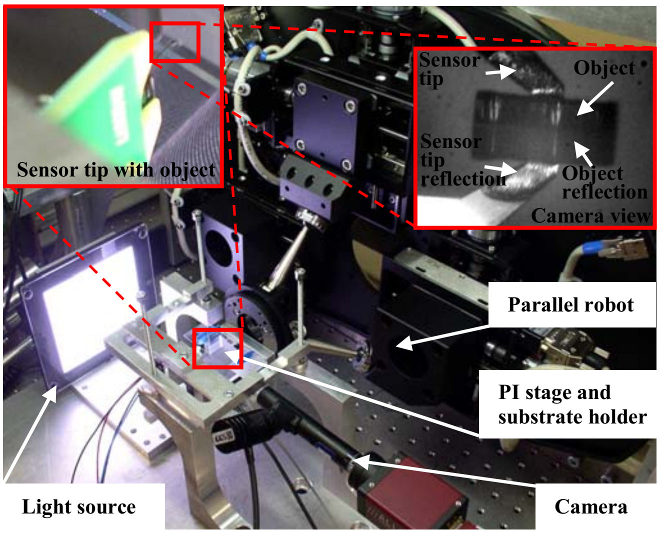

FIG. 2. Picture of the experiment setup for the pull-off force measurement.

Based on the system setup above, the pull-off force measurement is carried out. After the orientation between the two surfaces to be measured is fixed by the parallel robot system, the piezoelectric stage will move one object along the normal direction towards to the other object until the preload (55 µN) is reached. In the subfigure "camera view" of FIG.2, the contact between two objects is shown, when the maximum preload is applied. The pull-off force is recorded as a displacement-force curve, in which the micro-force sensor's value is a function of the relative distance between the two surfaces. FIG. 3 shows a typical curve of pull-off force measurement from the current data. The velocity along the normal direction to the micro-surface is set to 1 µm/s during the approaching and retracting process. The micro-force sensor tip with the micro-object deflects toward the surface fixed on the piezoelectric stage in the period of retracting process due to adhesion force before the surface on the tip breaks the contact with the other surface. At a so-called "jump-off" point, the tip goes through the lowest point in the force versus distance curve with a complete losing the contact with the surface, which is the pull-off force point.

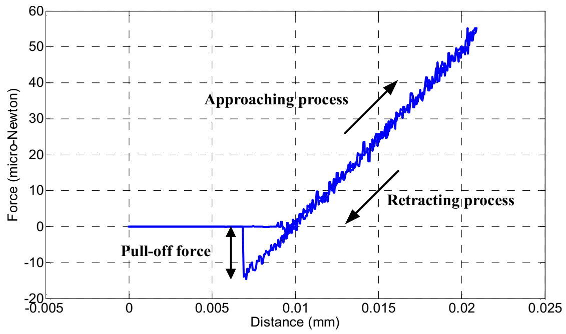

FIG. 3. A typical curve of pull-off force from actual measurement data.

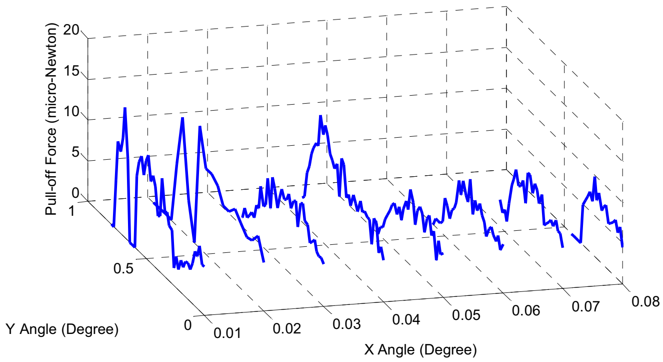

FIG. 4. An atlas of the pull-off force distribution versus the double-axis orientation.

For the pull-off force, it is known that its value is the function of the contact surfaces between the objects. Especially, for the pull-off force between the planar objects, its value is also influenced by the orientation between the surfaces. Therefore, a series of experiments is further implemented to show orientation is one of the influence effects for the plane-plane contact. For the experiments, the preload is kept as 55 μN and constant for different orientation configuration although no effect of the preload on the pull-off force is detected during the tests. The pull-off force measurement will be performed, every time the orientation between the surfaces is changed, in which the orientation variation step is fixed as 0.01^{o}. In fact, the variation step of the orientation can be further fine-adjusted since the rotational resolution of the robot system is 0.0005^{o}. Based on the measurement results, FIG.4 shows a local atlas of the pull-off force distribution versus the orientation between the surfaces. This figure shows that the orientation really influences the pull-off force between the planar contact objects, although the orientation variation is only set to 0.01^{o}. On the other hand, the experiment based on the measurement setup shows that our proposed system is competent for the pull-off force investigation, which can be extended to a series of plane-plane contact micro-force research.

IV. CONCLUSION

This paper introduces a new scientific platform which can be utilized in the field of micro-force measurement. This platform integrates a high precision six-degree-of-freedoms parallel robot and a commercial micro-force sensor. The integrated system can provide full degree-of-freedoms motion between the objects to be measured, which can realize relatively complicated plane-plane contact micro-force (friction force, adhesion force and interaction force etc.) measurement. The validation of the proposed system is demonstrated via the implementation of pull-off force measurements.

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